Sensing Surrounding 3-D Space for Navigation of the Blind

BY NIKOLAOS BOURBAKIS

The number of blind and visually impaired individuals in the USA is estimated to be more than six million.

–N. Bourbakis

A Prototype System Featuring Vibration Arrays and Data Fusion Provides a Near Real-Time Feedback

During the last decades, several research efforts have been directed toward providing better accessibility and navigation to blind individuals in their living environment by developing new devices and information technology scientific methodologies [1]–[15]. However, there is still a need to overcome navigation barriers encountered by individuals who are blind. Until these barriers are eliminated, the blind and visually impaired individuals will continue to be underrepresented. The analytical abilities of people with visual disabilities should not be disregarded, since there is no evidence that this population does not possess the same range of abilities as the rest of the population. On the other hand, the lack of opportunities to develop and use those abilities will certainly limit their employment advancement.

A range of adaptive technologies and devices has evolved since the 1960s to assist people who are blind in dealing with a variety of situations. The primary drawbacks included inconsistencies in feedback depending on various conditions (such as weather), possible disorientation caused by overuse of the sound space, and the fact that the information such devices provided was redundant to what the individuals could discern on their own in a more efficient manner using a cane or guide dog. The main drawbacks of existing assistive devices are the cumbersome hardware, the level of technical expertise required to operate the devices, and the lack of portability. These technological advances do not facilitate unobtrusive indoor navigation and learning from the environment. This limits employment and social opportunities for blind and visually impaired individuals. In summary, these technological advances target specific functional deficits but largely neglect social aspects and do not provide an integrated, multifunctional, transparent, and extensible solution that addresses the variety of challenges (such as independence) encountered in lives of blind people everyday.

This article presents a two-dimensional (2-D) vibration array for detecting dynamic changes in three-dimensional (3-D) space during navigation and provides these changes in real time to visually impaired users (in a form of vibration) to develop a 3-D sensing of the space and assist their navigation in their working and living environment. This vibration array is a part of the Tyflos prototype device (consisting of two tiny cameras, a microphone, an ear speaker mounted into a pair of dark glasses and connected into a portable PC) for blind individuals. The overall idea is of detecting changes in a 3-D space is based on fusing range data and image data captured by the cameras and creating the 3-D representation of the surrounding space. This 3-D representation of the space and its changes are mapped onto a 2-D vibration array placed on the chest of the blind user. The degree of vibration offers a sensing of the 3-D space and its changes to the user.

Other Navigation Projects

Some other relevant projects with navigation capabilities are discussed in this section [4], [7], [12]–[14], [16]–[31]. In the University of Maryland (UMD) project,

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researchers at the UMD attempt to establish a sound-based system training the blind user to be familiar with the level of the pitch when the user comes closer to obstacles (higher pitch for close obstacle and low pitch for far away obstacle). The major part of this project is the training of the blind user to a variety of pitch levels that correspond to various distances from existing obstacles in the traveling space. The UMichigan projects are two computerized devices based on advanced mobile robotics obstacle avoidance technologies. The first device (NavBelt) is worn by the user like a belt and is equipped with an array of ultrasonic sensors. It provides acoustic signals via stereo earphones that guide the user around obstacles or displays a virtual acoustic panoramic image of the traveler's surroundings. One limitation of the NavBelt is that it is exceedingly difficult for the user to comprehend the guidance signals in time to allow fast walking. The second device, GuideCane, effectively overcomes this problem. The GuideCane uses the same mobile robotics technology as the NavBelt but it is a wheeled device pushed ahead of the user via an attached cane. When the GuideCane detects an obstacle, it steers around it. The user immediately feels this steering action and can follow the GuideCane's new path easily and without any conscious effort. The FIU project is a computer-connected eye-gaze-based human-computer interface. It receives images from the environment and uses the computer to process them.

The AIR is an experimental system for the conversion of images into sound patterns. The system was designed to provide auditory image representations within some of the known limitations of the human hearing system, possibly as a step toward the development of a vision-substitution device for the blind. The application of an invertible (one-to-one) image-to-sound mapping ensures the preservation of visual information. The system implementation involves a pipelined special-purpose computer connected to a standard television camera. The time-multiplexed sound representations, resulting from a real-time image-to-sound conversion, represent images up to a resolution of 64×64 pixels with 16 grey tones per pixel. A novel design and the use of standard components have made for a low-cost portable prototype conversion system having a power dissipation suitable for battery operation. Computerized sampling of the system output and subsequent calculation of the approximate inverse (sound-to-image) mapping provided the first convincing experimental evidence for the preservation of visual information in the sound representations of complicated images. However, the actual resolution obtainable with human perception of these sound representations remains to be evaluated.

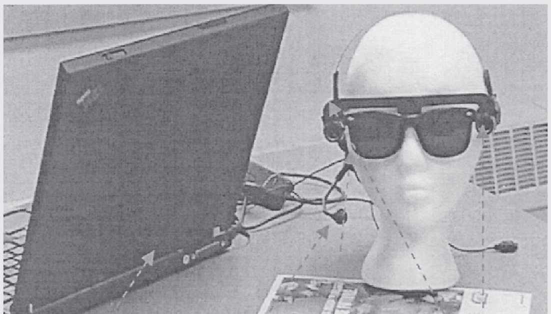

Fig. 1. The cameras attached to dark glasses, the microphone, and the ear speaker for the Tyflos prototype.

The Tormes system is a computer with a Braille keyboard and satellite navigation technology that gives verbal directions. This personal navigator was presented to the press in Madrid recently. The European Space Agency (ESA) was involved in this event because ONCE and ESA are already working on how to improve Tormes. The accuracy given by GPS is not precise enough and not guaranteed. A new tool developed by ESA could be the breakthrough: European Geostationary Navigation Overlay Service (EGNOS). EGNOS corrects the GPS signals and gives an accuracy of 2 m while GPS provides an accuracy of only 15–20 m. It also warns the users of any problem with the signal, thus giving integrity information. A similar project has the option to access indoor a priori information (like room structural design) from a database [14].

Also, several sound- and sonar-based systems or methodologies were presented at the World Congress for Blind 2005, held in Baltimore, Maryland, at the National Federation of the Blind [16]–[32]. All these systems are very good; however, they offer no hands-free navigation or ear-free hearing, and several groups of blind users have expressed concerns for their usefulness (based on group discussions with blind individuals). Some visually impaired have also expressed their disappointment with the sound-based systems because of the continual hearing of the pitch sounds in their ears, while some others have concerns based on the bulky appearance of these devices. Thus, an acceptable solution is a wearable device in a very small size attracting no attention, capable of, in a friendly way, offering additional information extracted from the surroundings and assisting them with hands-free navigation in their working and living environment. Also, other human factors that influence the selection and operation of the 2-D vibration patch came from discussions with a group of visually impaired individuals. That is why our system is different from the other projects and the issues mentioned earlier represent the motivation for the design and development of the Tyflos prototype.

The Tyflos System Prototype

The main role of the Tyflos mobility assistant is to capture the environmental data from various sensors and map the extracted and processed content onto available user interfaces in the most appropriate manner. The Tyflos prototype will integrate a wireless handheld computer, cameras, range sensors, GPS sensors, microphones, natural language processor, text-to-speech device, and a digital audio recorder (Figure 1). The audiovisual input devices and the audio output devices can be worn (or carried) by the user [1], [15]. Data collected by the sensors are processed by the Tyflos modules, each specialized in one or more tasks. In particular, it interfaces with external sensors (such as GPS, if applicable, range sensors, etc.) as well as the user, facilitating focused and personalized content delivery. The user communicates the task of interest to the mobility assistant using a speech-recognition interface.

The preliminary design and the development of the Tyflos prototype is already being carried out by the author (see Figure 1). This prototype consists of two cameras, a range scanner, an ear speaker, a microphone, a speech synthesizer, and a portable computer. This device is currently being evaluated by students with visual disability. The visually impaired students' feedback is being used in identifying the design requirements. The mobility prototype is based on the integration of several software components that reflect the methodologies presented here.

Tyflos Methodologies

Here we present the methodologies needed for the project for showing team expertise and real feasibility for achieving the main goal, which is the safe assistive navigation of a visually impaired person in the living or working space.

Region-Based Segmentation

Segmentation is a very important and difficult step for image analysis and computer vision, and many algorithms have been developed [9]. Here, we intend to use our fuzzy-like reasoning segmentation (FRS) method [10] that offers a light model as one of the segmentation factors. Its result is more accurate in terms of perception and more suitable for later reconstructing work. The FRS method has three stages (smoothing, edge detection, segmentation, and local-global graph synthesis of regions with common features). The initial smoothing operation is intended to remove noise. The smoother and edge detector algorithms are also included in this processing step. The segmentation algorithm uses edge information and the smoothed image to find segments present within the image. Finally, the local-global graph is used to synthesize (merge) those regions with common features, such as neighbors with similar RGB values, etc. In addition, the FRS methods eliminate highlights and shadows to some degree.

Range Data Conversion

The output from the laser scanner (or a range sensor) is a 2-D matrix of values regarding how far the laser scanner is from the surrounding environment that had been scanned [2], [5], [33]. Once the final 2-D distance matrix is complete, several preprocessing steps are required before a 3-D representation may be displayed: height adjustment for proper distances, depth compensation (sample smoothing), matrix expansion (if necessary), and polygon surface definition.

Height adjustment is necessary because the actual laser measurements represent distances from the laser unit to a point on the object surface. For example, if we are working with objects on the floor plane, the furthest distance measured would be the furthest point located on the floor plane. The sample data must be adjusted by subtracting all points from this furthest distance, which results in the object's true height being determined.

Depth compensation (sample smoothing) involves adjusting the laser range data to compensate for the effects of increasing laser measurements for areas on the same plane. If a scanning of a cube object is performed, which is directly below the laser (on the ground plane), the closest point would be the center of the cube and measurements would continually increase toward the extents of the cube. This would result in the cube object having a rounded top plane, since the nearest point would be its apex, and this would result in a rounded surface, which is not correct. The laser measurements can be corrected if we allow for a slight tolerance among successive sample points, thereby ensuring that a smooth flat surface is generated when a level plane is encountered.

Matrix expansion may be necessary since the resolution of the laser output is usually lower than that of the image produced by a camera. If the matrix resolution is 32×32 and the camera image is 128×128, this would result in a matrix expansion by a factor of four for proper alignment. If these resolutions do not factor into one another evenly, interpolation must be performed to achieve a 1:1 mapping.

Once the previous steps are complete, we are ready to actually define the surface as a series of adjoining polygons for display. Each of the 2-D points of an $N \times N$ matrix represents a vertex edge, and then an edge list is generated that represents the surface contour among the $(n - 1) \times (n - 1)$ polygons. Note: On polygon conversion, the number of sample points from the laser output always results in each row having one less polygon than the number of sample points and also one complete row of values missing. To compensate for this scale-down effect, during preprocessing, we add one additional sample at the right end of each column and an entire additional row at the bottom of our sample. The sample values at these additional points are assumed to have an identical value as their predecessor. This allows a good 1:1 mapping.

Fusion Methodology

In the literature, there are several multisensor fusion [34]–[47] and mapping methods [48]–[51]. The fusion methodology proposed here uses the more accurate fuzzy segmented data to improve the resolution of the range data. The method involves combining polygon surface definition derived from the laser output and applying the segmented camera image [Figure 2(a)]. Steps necessary before the fusion process are as follows:

- For the laser scanner
  1) obtain laser range data
  2) convert range data to height or depth data (depth compensation/sample smoothing)
  3) generate an index matrix
  4) expansion of index matrix (if necessary)
  5) generate polygon surface definition.
- For the camera image
  1) generate a histogram
  2) segment the captured image
  3) fuse the index matrix and the segmented camera image.

Range data provides information regarding how far the laser is from the environment it is scanning. It does not directly give the height or depth of the object, which is necessary to create a 3-D model of the space. Therefore, several steps are needed to convert the range data to depth or height. First, the range data is used to identify potential objects. Second, the object under investigation must be classified as being on the floor plane or on the wall plane. Objects on the floor plane have a height whereas objects on the wall plane have a depth.

An index matrix is generated once the height and depth values are calculated. An index matrix eliminates the slight measurement and truncation errors by grouping values that are very close in magnitude and assigning the groups the average of their values. Note that with flat objects this will be a single value. For sloping objects, the index value will change in a step-like fashion.

Next the values of the index matrix are adjusted by the color-segmented image. An assumption in this process is that the color changes at different heights. With flat surfaces, the color will dictate how the data are changed. For flat objects, if two adjacent index values are different and they both have the same color value, this indicates an edge. Then, the adjacent index values with the same color are evaluated to determine the new index value at the boundaries. If the object is determined to have a slope, then the procedure is nearly the same as the flat surface method. However, fewer adjacent index values are evaluated because the local index changes too rapidly. Since the color changes may not be evident on gradually sloping surfaces, the color is only used to determine the edges of the object. Once all the index values have been adjusted the color-segmented matrix and the index values are combined to get the final 3-D model.

Example. We graphically present the fusion of the laser and camera image segmented data. The range data matrices are 32×32 and the camera images are 128×128. Figure 2(b) represents the initial 3-D representation of a range matrix with the addition of noise or spikes that may be considered inaccuracies of the laser scanner. Figure 2(c) is the expansion of the index matrix. Figure 2(d) shows the original image without segmentation used in the first example. Figure 2(e) is the final fused image; notice that the error in the laser measurements was corrected by the fusion process. In this simulation, only the floor plane was evaluated. The advantage offered by the fusion is the more accurate representation of the 3-D space without the false indication of a wall projection (i.e., movie or picture) or the clean glass door problems.

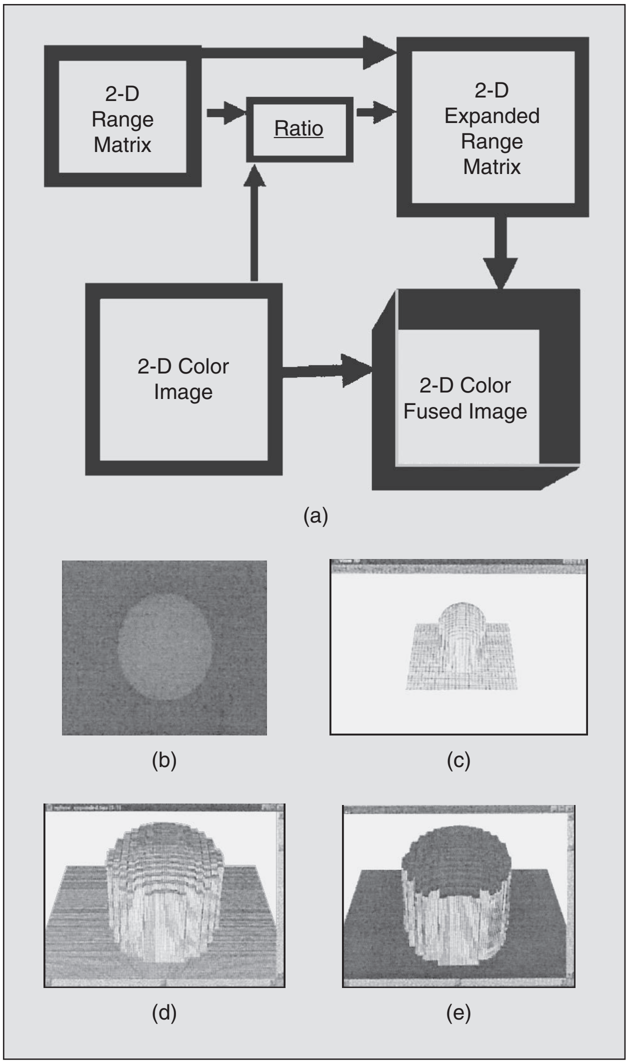

Fig. 2. (a) The diagram of the fusion process. (b) Original camera segmented image. (c) Initial range matrix with noise. (d) Expanded index matrix. (e) Final fused 3-D image (perceived view).

The 2-D Vibration Array

The morphological (or topological) 3-D information generated from the 3-D perceived space map, from the fusion method mentioned earlier, is converted into vibration sensing on a 2-D vibration array attached to the user's skin, for instance, on the stomach or chest area, viewing the front direction that the user has to navigate him/herself. In particular, each pixel (or a small predefined region from the 3-D perceived depth image) is represented by a distance from the surrounding borders of the environment. Thus, each distance is converted into an analog current that quickly vibrates a cell of the 2-D vibration array. Each cell is appropriately selected to quickly change status (no vibration, slow vibration, fast vibration) and appropriately guide-inform the user about the 3-D surrounding space. The type of vibration motors used in the patch is the Lufa-10b451 miniature sensor. The range of the vibrating sensation is controllable and predetermined to cause no harm to the user. On the basis of the degree of the vibrating sensation and the location of this sensation on the 2-D vibration array, the user gets a general idea about the 3-D representation of the space in front of him or her. In other words, the user gets an idea if there are obstacles in front of him or her and on what location and direction, based on the vibrating sensation on the particular cells of the 2-D array. Also, the faster vibration on certain vibration cells indicates that an obstacle is closer to the user. Thus, when the user feels a continuous vibrating sensation coming from the right and left edges of the 2-D array and no vibrating sensation in the middle, that means there is free open space in front of him or her for navigation. The placement of such array on the stomach or chest area offers several advantages to the user, for instance, free hands, since it is hidden under the cloths, and its location is well aligned with the camera's direction. Figure 3 briefly shows the processing steps required for the generation of the 2-D vibrating array measurements, whose degree of vibration indicate and represent the depth of the scenery view in front of the user. Note that the selection and use of vibration arrays is preferable to heating arrays because of their reliable responses and less sensitivity to pressure and manipulation changes.

Figure 4 shows the location of the 2-D array patch on the human's chest.

In addition, other 3-D depth representations generated only from video images involve false indication of depth, for instance, posted images of highways on walls, or clean, glassy

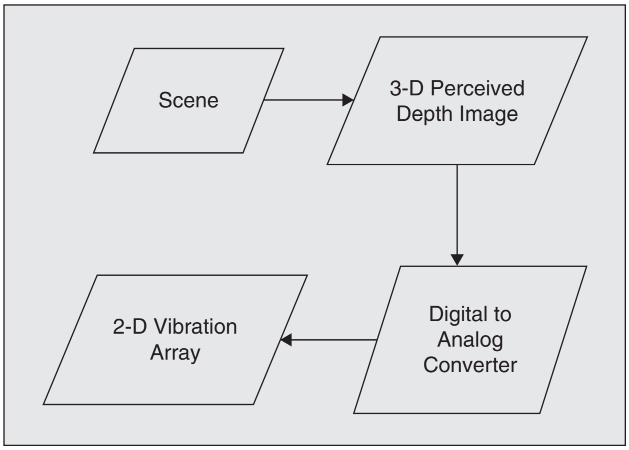

Fig. 3. The diagram of the steps needed for the generation of the 2-D vibrating array.

doors where an image processing system will generate a fake 3-D depth impression. In our system, by fusing different modalities, we provide more accurate and real representation of the 3-D surrounding environment.

Simulated Results: Motion Detection and Tracking

The proposed scheme is employed for detection of moving objects in the image sequence. This is accomplished by spatiotemporal diffusion and kernel-based motion detection where the moving objects are segmented using a region-growing segmentation algorithm [11]. In particular, a new motion activity measure is used based on the idea of spatiotemporal anisotropic diffusion. According to this approach, the areas that are spatially and temporally homogeneous are diffused more than the spatiotemporal edges. The new motion activity measure is accordingly derived from the total amount of diffusion in the spatiotemporal domain. The result of this process is a motion activity map, where higher values denote the moving pixels. To remove the outliers and detect the moving objects consistently, a kernel density estimation method is used. This is accomplished by estimating the probability density function using Parzen kernels. The employed feature space is composed by the motion activity values and the corresponding spatial coordinates. The final moving areas are detected in two steps. First, the probability density map is inverted, the watershed algorithm is subsequently applied, and the regions of the low-valued minima are finally selected to detect moving regions.

Figure 5 shows video processing (motion) results. Figure 6 shows the representation of the vibration array for a depth image.

Simulated results are presented from the example showing the generation of the 2-D vibration array for proving the concept [see "The 2-D Vibration Array" section; an obstacle area bordered by a red line and vibrations generated on the 2-D vibration array (red area close, orange area (human body) not too close)]. The results obtained with our experiment from the fusion to the vibrating array are near real time (one frame/second). Note that a typical real-time walking style takes one to three steps/second (see Figure 7).

Learning Vibration Patterns via Training for Sensing the 3-D Space

The learning process used here has two phases: (phase I) training the blind user via simulated vibrations and (phase II) testing the training in real environment. During the training sections of the phase I, the Tyflos 2-D vibration array generates a variety of vibration patterns on the body of the blind user, who is called to respond by voice and decide from which directions (in front of him or her) there is or is not a moving obstacle or an open corridor. The variety of vibration patterns are

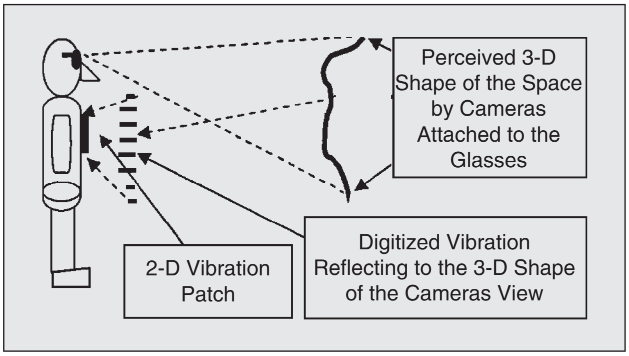

Fig. 4. The location of the 2-D vibration patch.

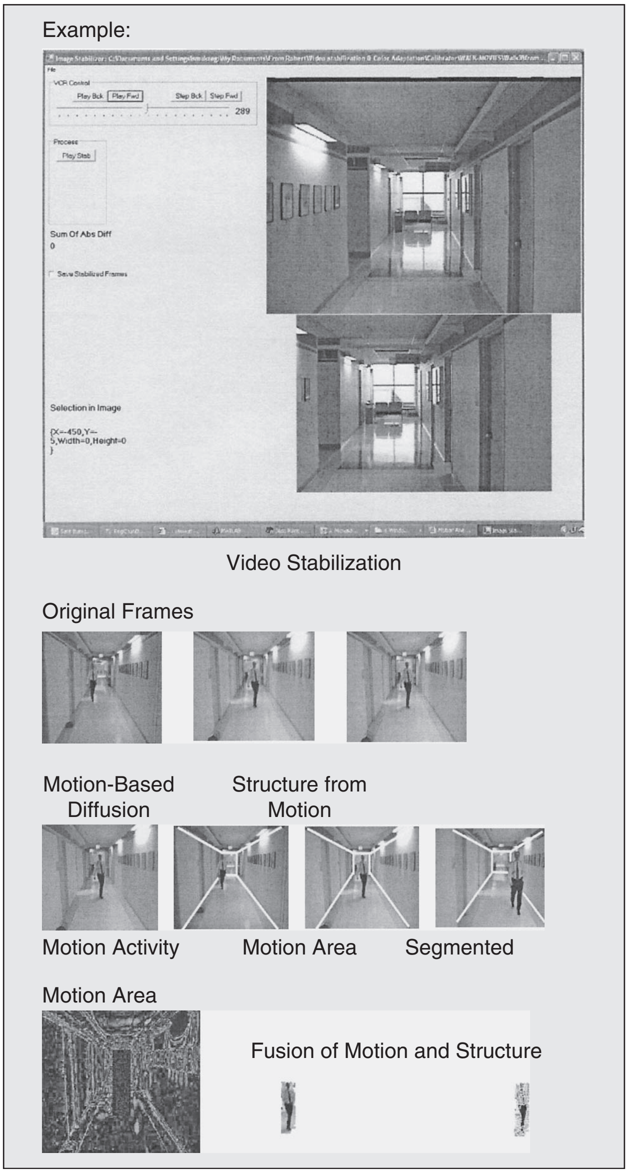

Fig. 5. Motion results from the moving camera.

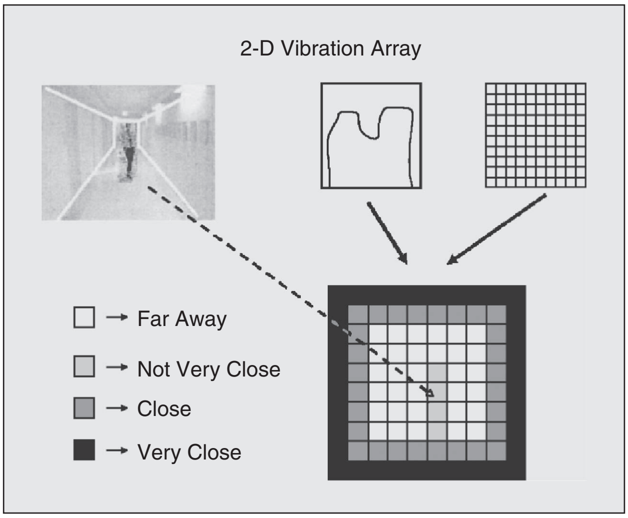

Fig. 6. Representation of the depth image in the vibration array.

generated by the VRL language that is stored in the portable PC. In Figure 8, the primitive vibration patterns (A,B,C, . . . ,R) of the VRL language and a small set of simulated vibration patterns generated by VRL as a synthesis of the primitive ones are presented. VRL is a simple language that generates 2-D patterns on a 2-D array [52].

During phase II, the blind user receives a training session in a real environment, where a variety of 3-D representations have been created by the Tyflos working team. During this session, the user has to correctly recognize the vibration patterns that correspond to real environmental 3-D representations. Results from phase I and phase II will be available after the completion of these sessions, which will last for six months.

Conclusions

A 2-D vibration array approach for assisting the navigation efforts of visually impaired individuals was presented. The results of the 3-D dynamic visual-range representation of a surrounding space were mapped onto a 2-D vibration array and the vibrating sensation offers to the visually impaired user the sense of the 3-D space. In other words, the 2-D vibration sensation is coming to partially replace the 3-D space vision loss for visually impaired individuals. Also, the selection of the 2-D vibration patch and the 2-D mapping technique on it were based on the decision made by a group of blind users. The results presented in this article are based on real tests and simulation. It is important to mention here that this project is in its first stage of evaluation, thus no statistical analysis of success and failure modes, and no sensitivity analysis of the proposed methodology with respect to varied environmental conditions, such as lighting (although the image segmentation method takes care of lighting issues) and multiple subjects, have been completed yet. The training of visually impaired user is in progress. The first statistical results are expected in a period of three to four months. Also, safety issues regarding the use of lasers represent a concern, and alternative sensors, such ultrasound, are under evaluation.

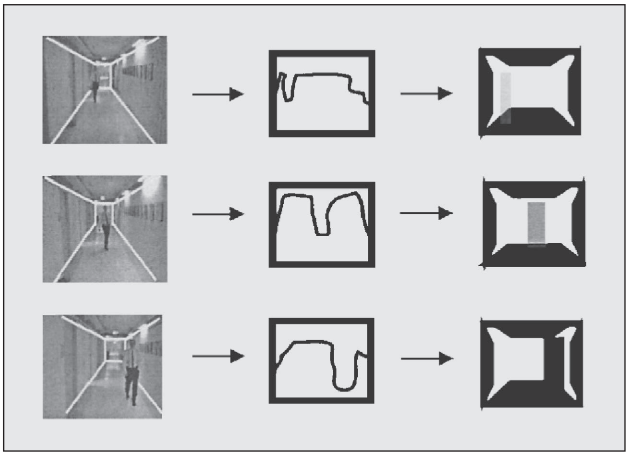

Fig. 7. Simulated results from video.

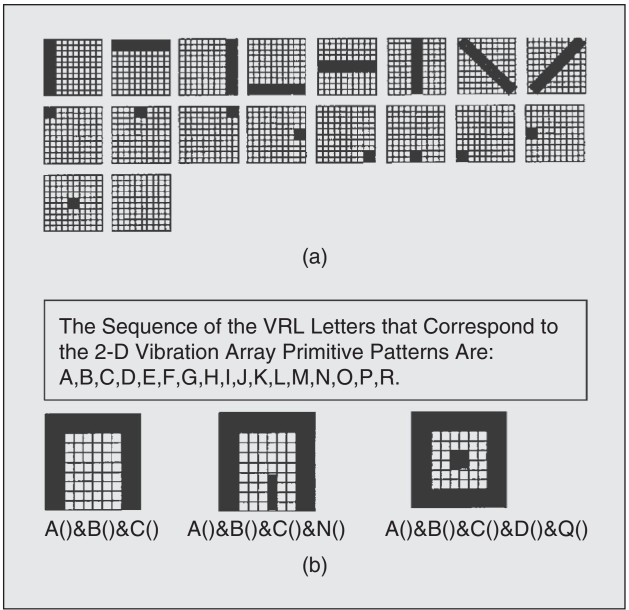

Fig. 8. (a) Primitive VRL patterns and (b) synthetic patterns using the VRL language.

There are several critical issues that we have to deal with, such as the computational time needed for the real-time execution of all the tasks necessary for the successful completion of the image processing, data fusion, and driving vibrations operations. Currently, we use a portable PC (HP zv5340us) that is capable of successfully completing the tasks mentioned earlier. However, some open problems remain, such as the real-time response of the vibration array and the user's real-time response to these vibrations. Thus, these problems represent important tasks to be evaluated during the training sessions with the real users, and answers will be available in the near future. It is also important to mention that if the visually impaired community will approve this Tyflos device, we intend to implement in FPGAs all the image processing, fusion, and data acquisition tasks to have real-time performance, taking into account that the expected navigation speed of a visually impaired individual will be up to three steps/second. The power conception will be associated with the potential of the batteries of the portable computer (notebook). Thus, the visually impaired user has to recharge the batteries after a certain time or carry additional batteries connected to notebook.

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